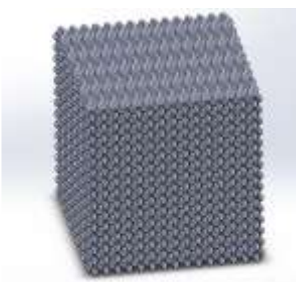
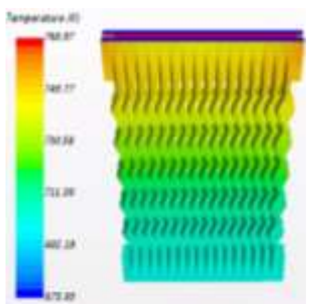
CHANGING WHAT'S POSSIBLE

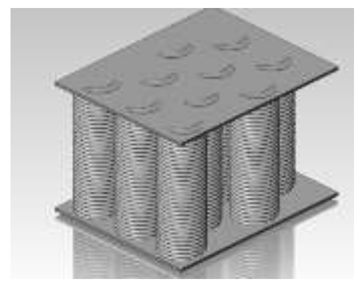
Development of Next-Generation Heat Exchangers for Hybrid Power Generation

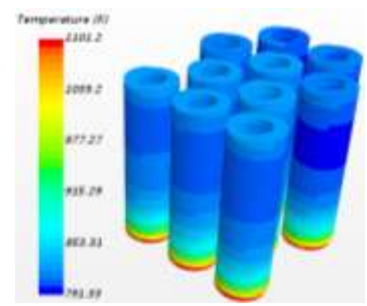
Kashif Nawaz, Oak Ridge National Laboratory

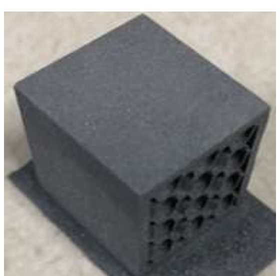
Design and development of a cost-effective high-efficiency, high temperature, ceramic/steel alloy heat exchanger.











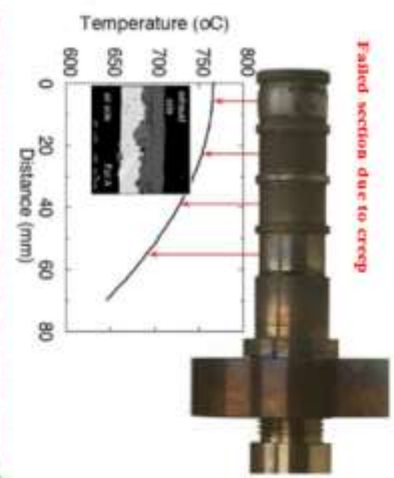
Project Overview

Fed. funding:	$1.0 M
Length	24 mo.

Team member	Location	Role in project
Oak Ridge National Laboratory	Oak Ridge, TN	Project Lead
University of South Carolina	Columbia, SC	System Integration

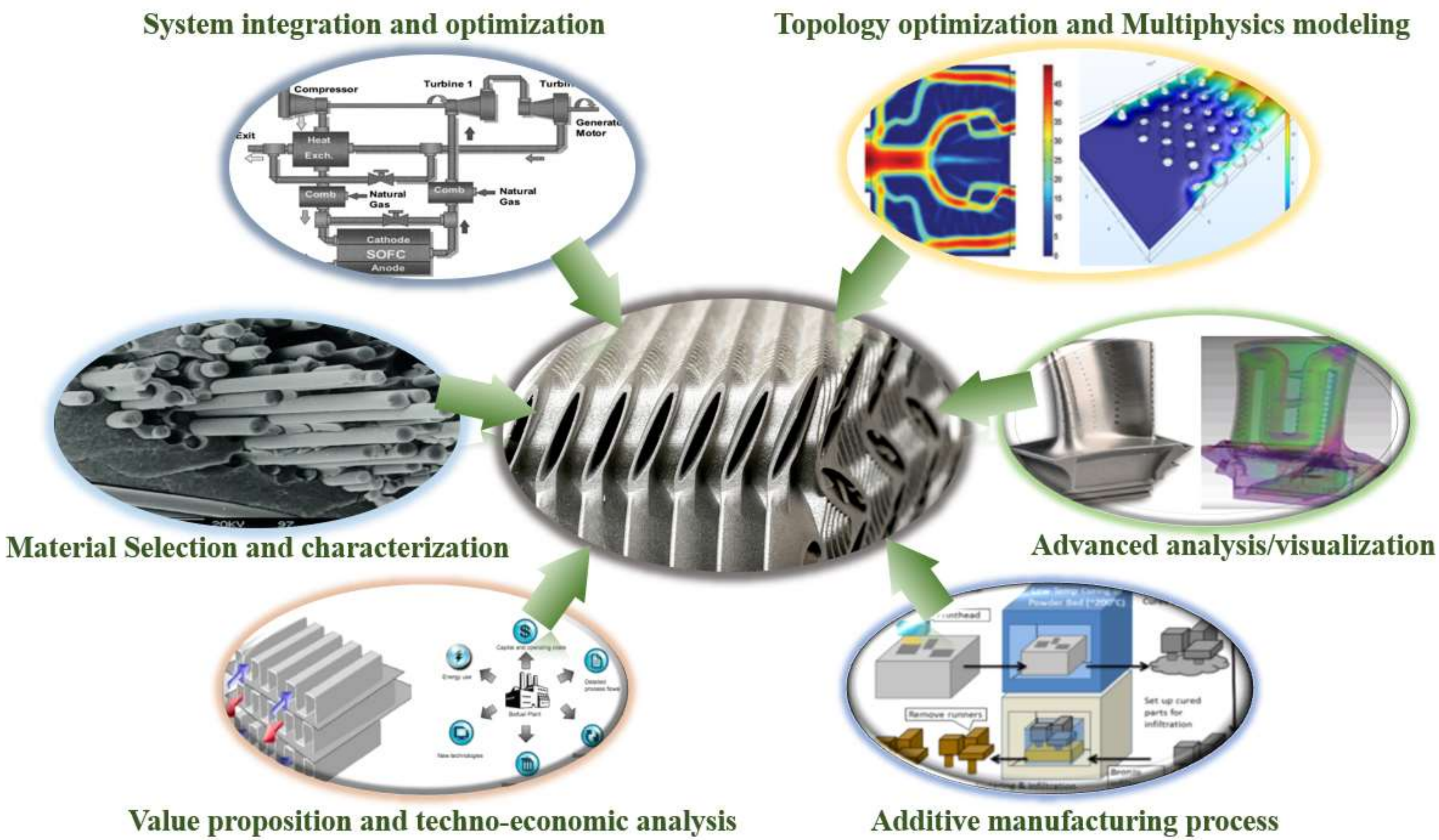
Topology Optimization

Development of Materials



Development of Manufacturing Process

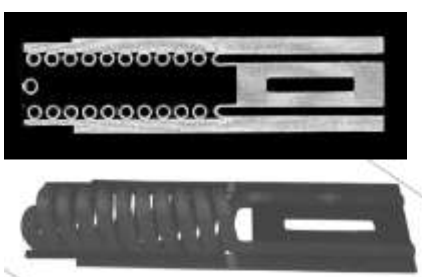
Solution Strategy

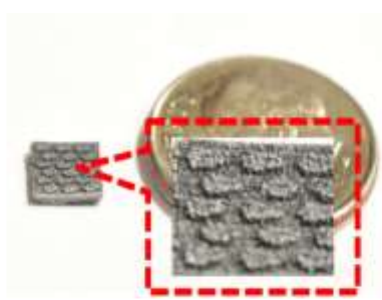


Innovation and Objectives

Innovation

- **High-performance computing:** achieve optimum solution
  - **Topology optimization:** maximize thermal-hydraulic performance
  - **Multi-physics modeling:** investigate thermal-mechanical conjugate problem
- **Additive manufacturing:** complex geometry and materials
- **Advanced visualization:** quality assurance and fracture analysis





Task outline, technical objectives

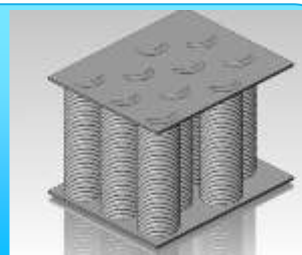
- **Design:** unprecedented thermal-hydraulic performance-Target 200% improvement UA from state-of-the-art.
- **Materials:** suitable thermal conductivity and sufficient mechanical strength at temperatures ~1000°C.
- **Manufacturing cost:** reduced by at least 30% compared to the state-of-the-art technology.

Tech-to-Market objectives

- Engage commercial entities: Isotherm Inc., Atrex Energy
- SOFC industry will be first target
- Stakeholders from additive manufacturing industry are onboard

Progress- Value Proposition

- Improved resistance to thermal fluctuations
- Design of headers is a challenge
- Modularity is possible
- AM is required to implement



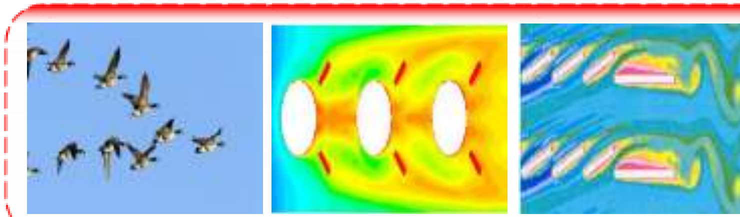
- Design of headers is a challenge
- Modularity is difficult
- AM is required for implementation
- 2/3-dimensional wavy design a simplified version

- Modularity is possible
- Commercially available foams can be deployed
- Conventional manufacturing process can be used.

$$Q = hA\Delta T$$

$$\frac{1}{UA} = \left(\frac{1}{\eta_o A h}\right) + R_{wall} + \left(\frac{1}{\eta_o A h}\right)$$

Improvement in Heat Transfer Coefficient



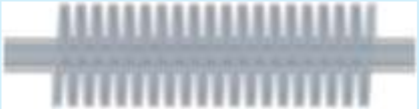
Improvement in Heat Transfer Surface Area

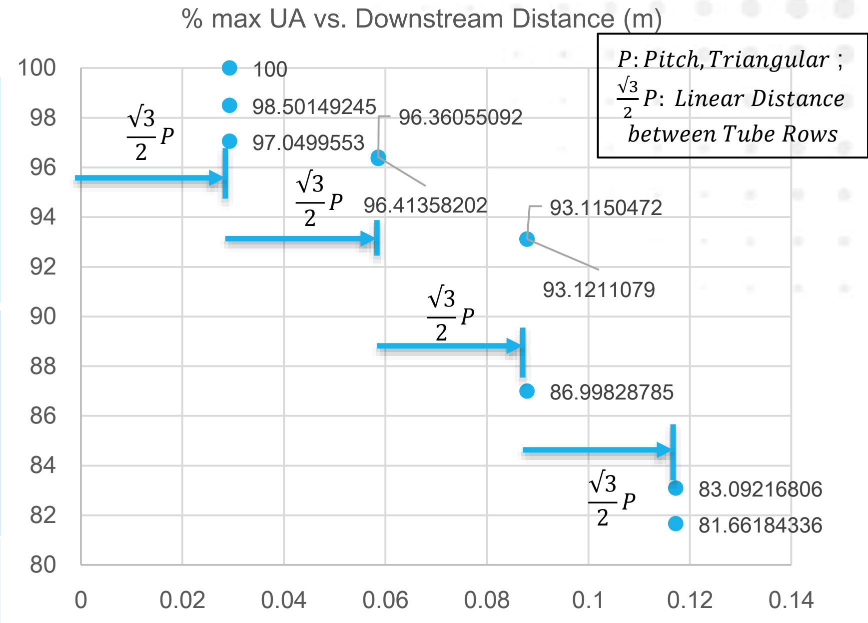
Heat transfer coefficient

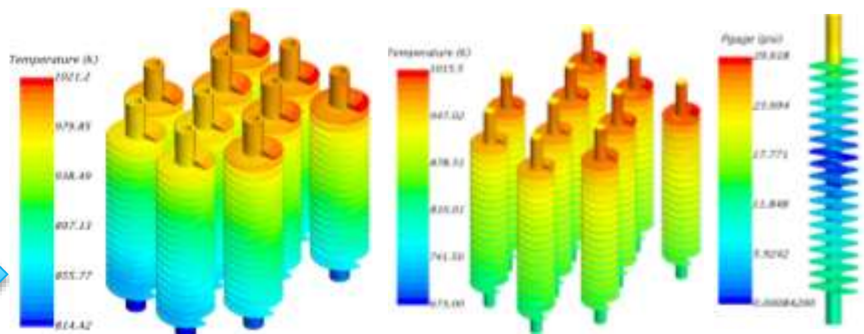
Pressure gradient

arpa·e
CHANGING WHAT'S POSSIBLE

Progress- Design Optimization

Rectangular/Hollow/Spiral 	Q= 5.2 kW	$\Delta P_s = 0.39$ psi $\Delta P_t = 18$ psi
Rectangular/Hollow 	Q= 5.95 kW	$\Delta P_s = 0.36$ psi $\Delta P_t = 27$ psi
Triangular/Hollow 	Q= 4.66 kW	$\Delta P_s = 0.43$ psi $\Delta P_t = 19$ psi
Triangular/Hollow/Spiral 	$\boxed{\text{Q= 6.11 kW}}$	$\Delta P_s = 0.29$ psi $\Delta P_t = 35.79$ psi





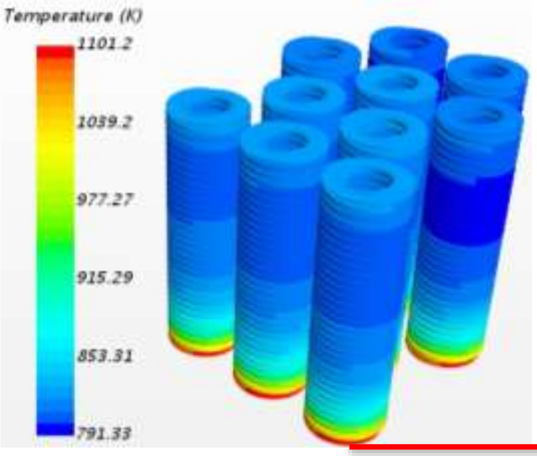
Infiltrated SiC (wall)
[814 K, 1022 K]

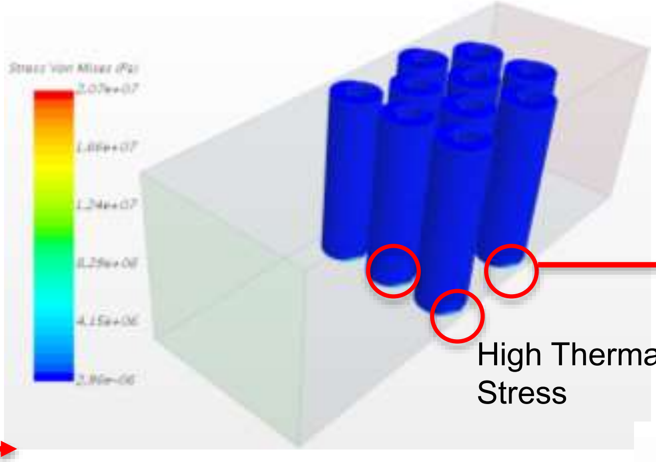
Air (tube-side, cold)
T = [673 K, 1016 K]
T_out = [916 K, 930K]

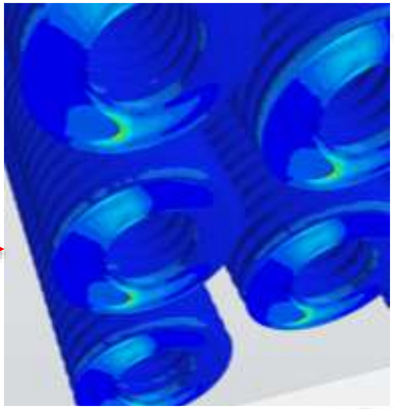
P_{in} = 11.67 psi
P_{out} = -24.12 ps
ΔP ~ 35.79 psi

Progress- Thermomechanical Optimization

- Obtain conjugate heat transfer solution
- Map to thermal expansion simulation
- Quantify structural integrity (stress, displacement thickness)

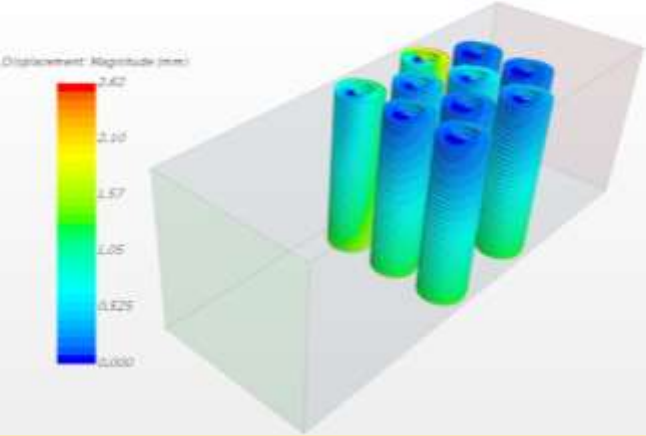






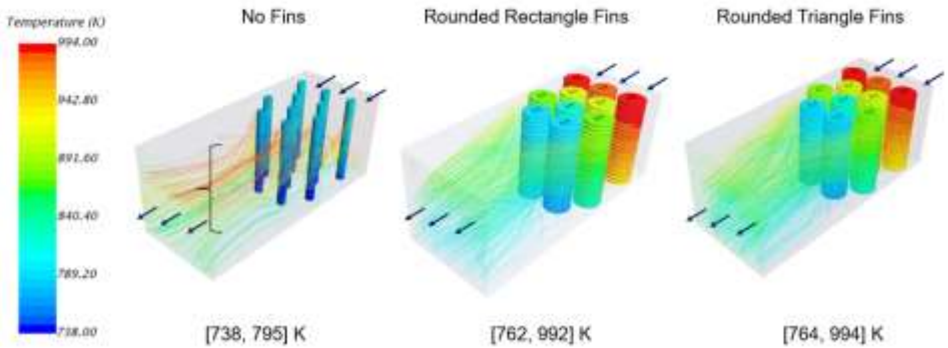
High Thermal
Stress

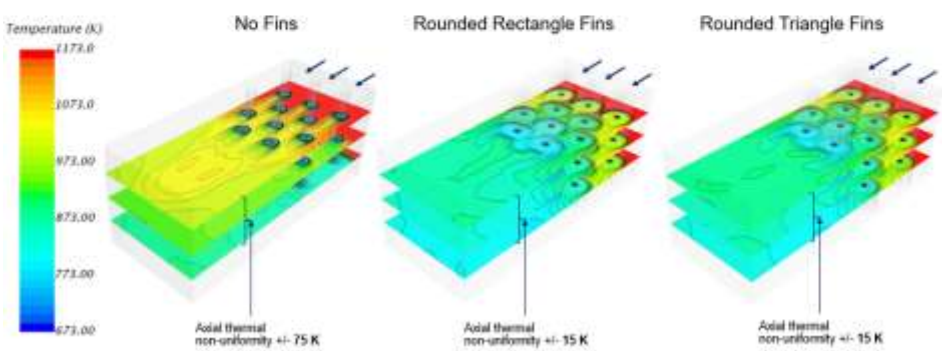
High Temperature

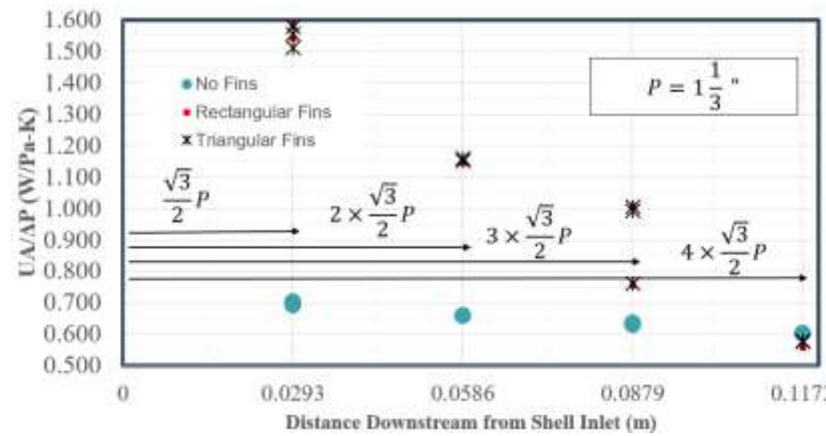


- Test if displacement thickness is within design limits

Progress- Design Optimization



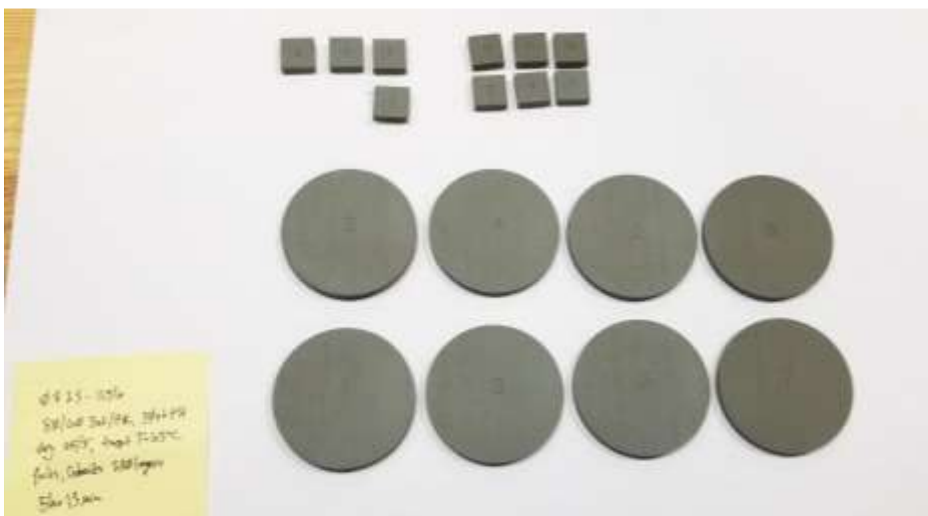




Progress- Manufacturing Process

Obtaining the best printing parameters for parts

- For testing post processing
- Prelude into large heat exchanger printing
- Dry time, saturation (or binder amount), and spread speed



Sample printing
(medium-sized printer, Innovent)

HxN printing
(largest printer, M-flex)

Progress- Manufacturing Process

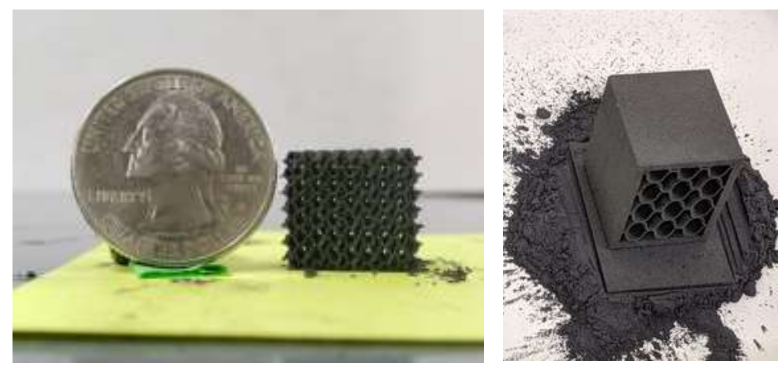
Using small puck and cuboid printing parameters (on largest printer) is not feasible

- Size of parts and binder choice become important
- Buckling, warping, and cracking can be issues

Printing process flow

Powder preparation → Printing Process and curing → Depowdering, Infiltration /sintering

Heat exchanger printing
(large-sized printer, M-flex)



Sample printing
(medium-sized printer, Innovent)

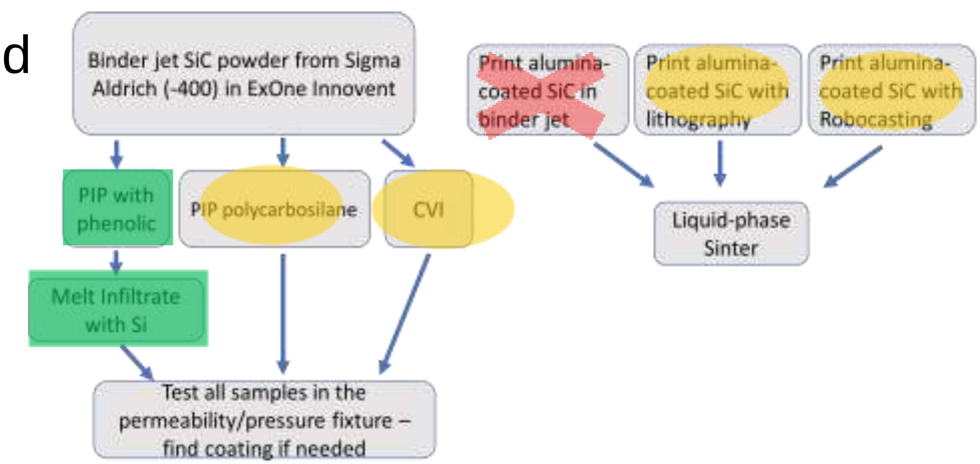
Progress- Manufacturing Process

- Goal: Make hermetically sealed, high SiC content part parts by 3D printing followed by subsequent infiltration processes
- Approach:
  - SiC printed pucks by binder jetting
    - Reactive infiltration with molten silicon
    - infiltration and pyrolysis of polymer precursor for carbon, followed by reactive infiltration with molten silicon
    - infiltration and pyrolysis of polymer precursor for SiC with SiC precursor PIPs
  - SiC sintering with sintering aid

= Achieved desired permeability

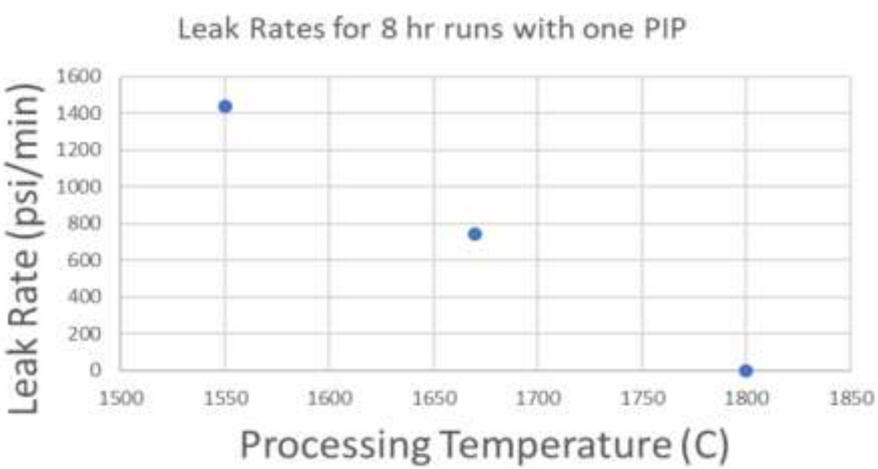
= Cannot make

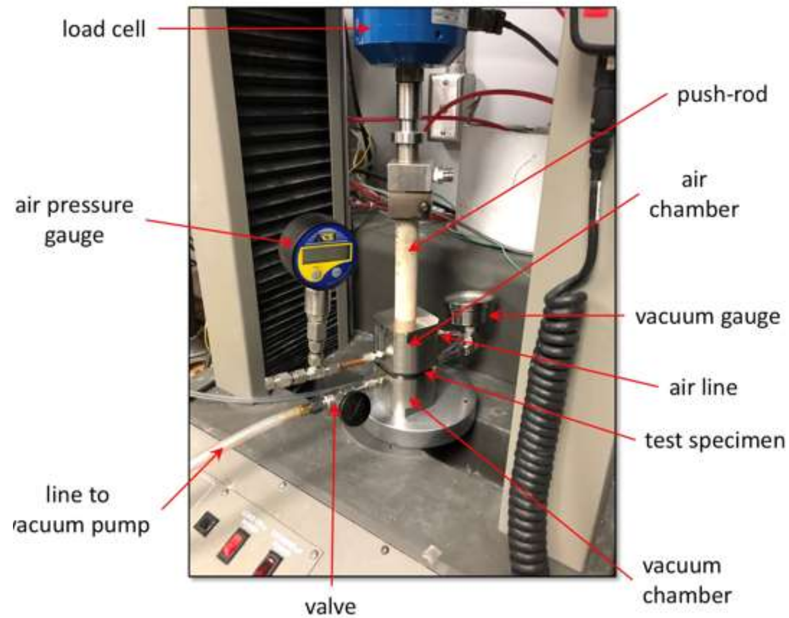
= In progress



Progress- Manufacturing Process

Molten Si Infiltration			
	2 hours	4 hours	8 hours
1550 °C			DONE
1670 °C	DNW	DNW	DNW
1800 °C	DNW	DNW	DNW
1 phenolic PIP			
	2 hours	4 hours	8 hours
1550 °C			
1670 °C	DONE	DONE	DONE
1800 °C	DONE	DONE	DONE
2 phenolic PIP			
	2 hours	4 hours	8 hours
1550 °C			
1670 °C			DONE
1800 °C		DONE	DONE

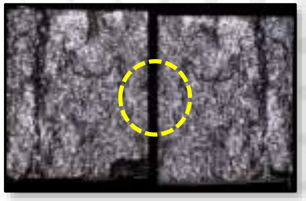




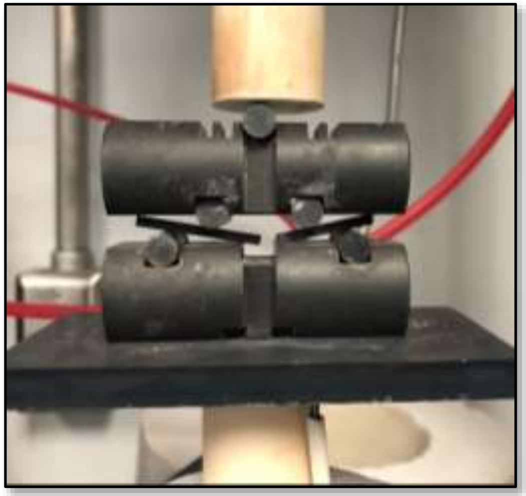
	Processing Temperature (C)	Leak Rate (psi/min)
8 hrs, 1 PIP	1550	1440
	1670	744
	1800	0.85
	intrinsic to tester	1.12
	overinfiltration of Si	1.16

Progress- Material Characterization

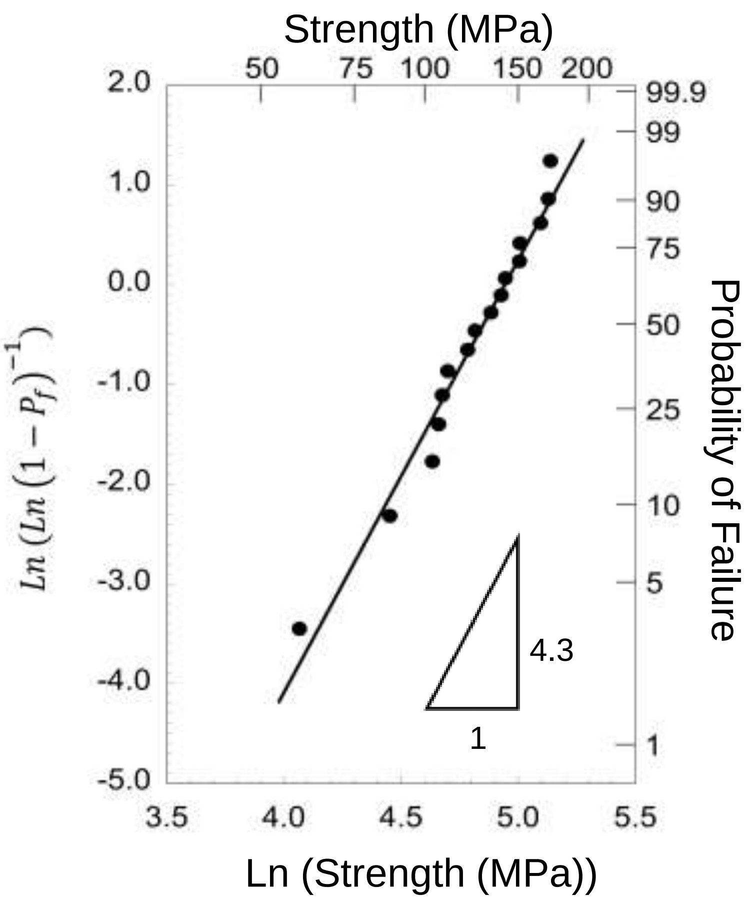
Mechanical Evaluation of Siliconized SiC Composites



Weibull Analysis of Flexural Strength Results at RT

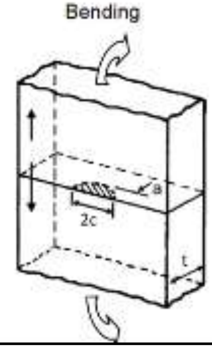


Flexural Strength



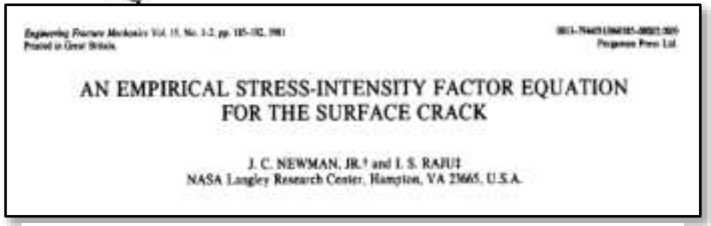
Progress- Material Characterization

Fractographic Analysis of Test Specimen to Determine Fracture Toughness



$$K_{Ic} = Y\,\sigma_f \sqrt{c}$$

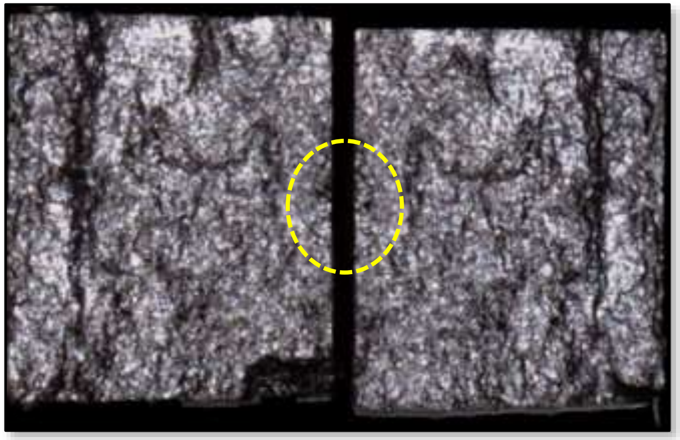
a	0.27 mm
2c	0.64 mm
Y	1.24
σ	162.2 MPa
K_{IC}	3.64 MPa-$m^{0.5}$

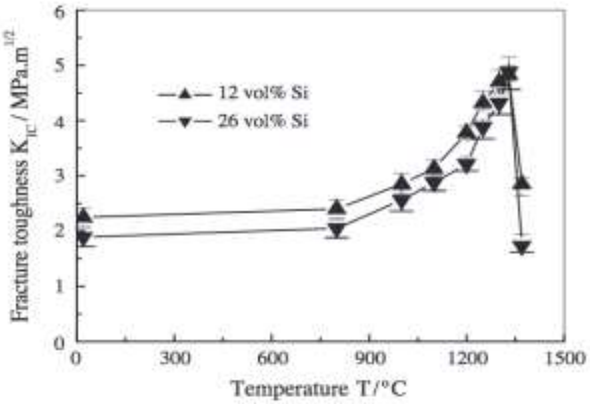


AN EMPIRICAL STRESS-INTENSITY FACTOR EQUATION FOR THE SURFACE CRACK

J. C. NEWMAN, JR. and I. S. RAJU

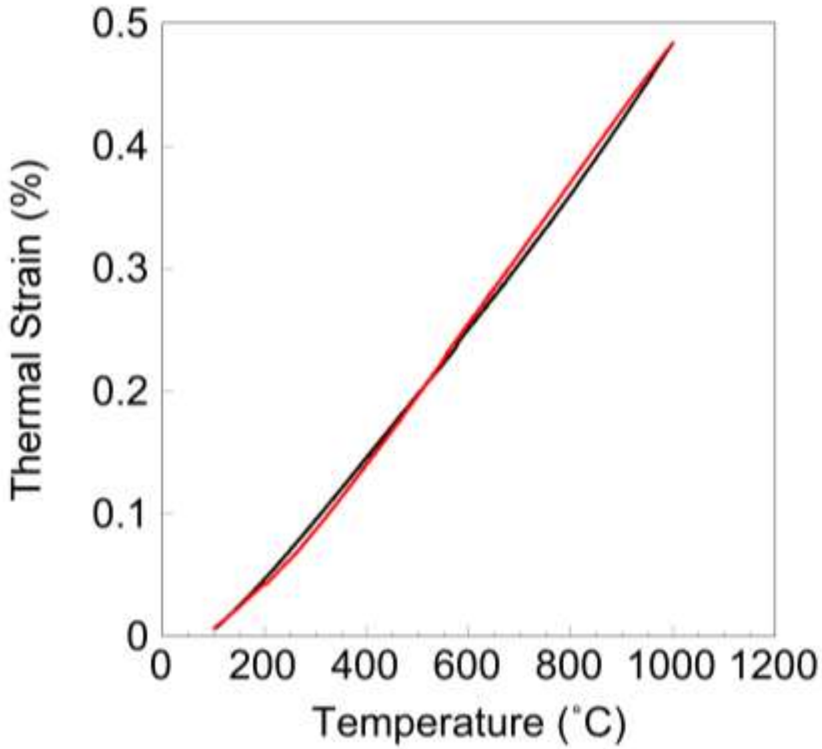
NASA Langley Research Center, Hampton, VA 23665, U.S.A.

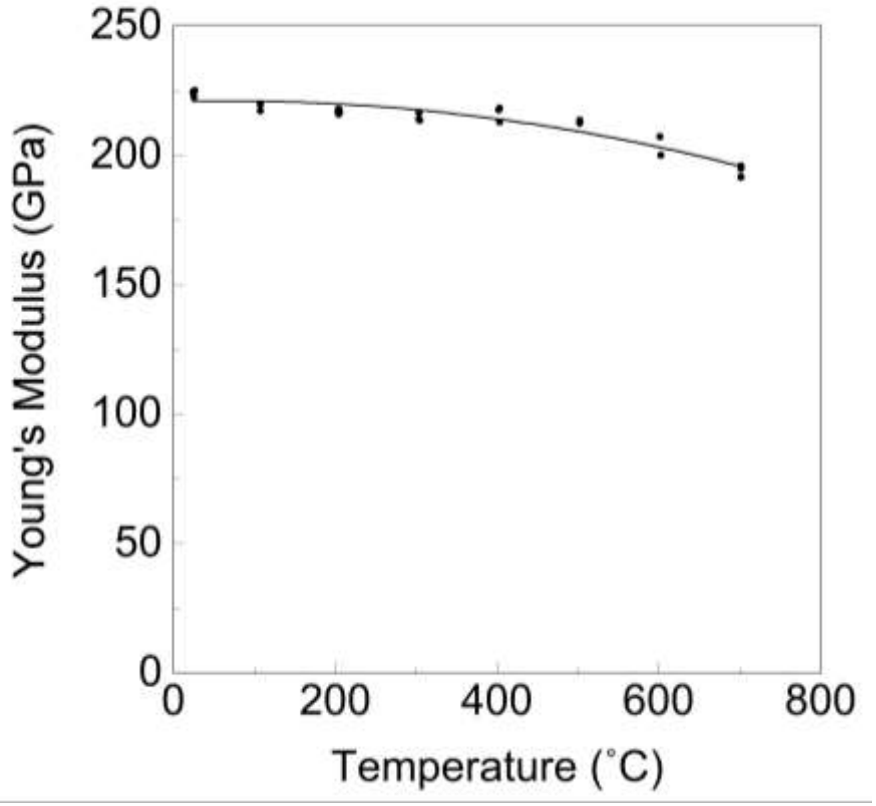




Progress- Material Characterization

Determination of Young's Modulus by Impulse Excitation and Coefficient of Thermal Expansion by Thermomechanical Analysis





Progress- Materials Characterization

CT scans of Coil HxN – tool for printing, finding defects

Isometric view

Video of scans in z-direction

Machine: Metrotom
Resolution: ~20 micron

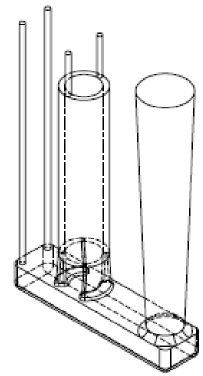
Progress- Materials Characterization

Preliminary assessment of AFA alloy developed at ORNL

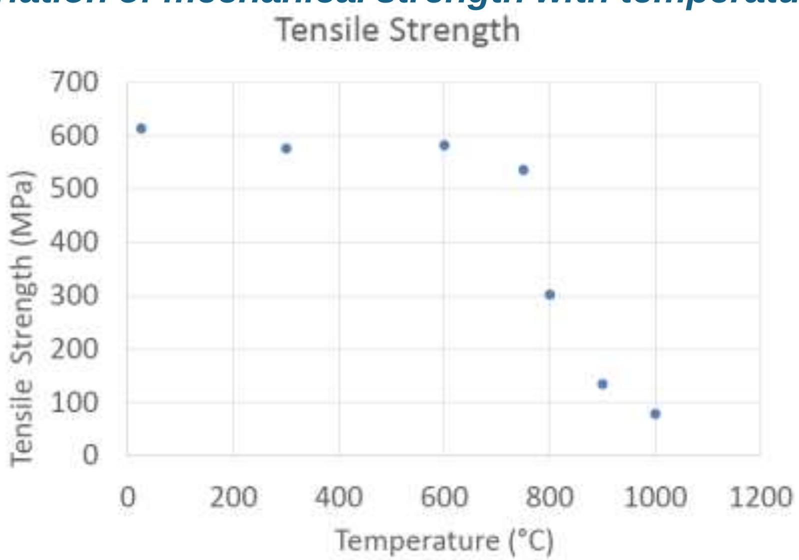
Alloy composition

Alloy	Fe	Cr	Ni	Al	Si	Hf	Y	B	C	Nb	Mo	W	Ti	Zr
HP (Baseline alloy)	36.80	25	35	-	1.25	-	-	-	0.45	1.5	-	-	-	-
#11A	33.87	25	35	4	0.5	0.15	0.07	0.01	0.4	1	-	-	-	-

Sand mold for casting



Variation of mechanical strength with temperature

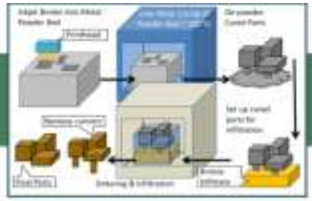


Major thermo-physical properties

T, °C	Specific Heat Capacity (J/g K)	CTE (x10^{-6})	Density (g/cc)	Thermal Conductivity (W/m K)	E (Gpa)
25	0.48	13.2	7.58	10.542	162.987
50	0.487		7.58	10.988	
100	0.498	13.9	7.56	11.809	159.750
200	0.522	14.34	7.53	13.529	154.700
300	0.542	14.67	7.49	15.303	150.080
400	0.563	15.01	7.46	17.149	143.470
500	0.584	15.29	7.42	18.855	137.690
600	0.605	15.72	7.38	20.763	132.790
700	0.624	16.35	7.34	22.687	126.630
800	0.644	17.92	7.28	22.737	118.220
900	0.665	18.56	7.22	25.017	112.130
1000	0.682	18.76	7.18	26.793	107.160
1100	0.705		7.13	27.722	

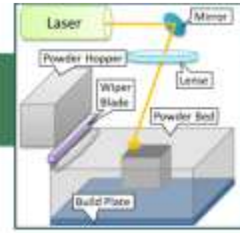
Progress- Development of cost model

Binder Jet

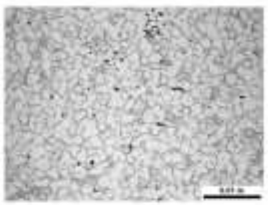


- High Productivity
- Low Maintenance
- Isotropic Properties

Laser

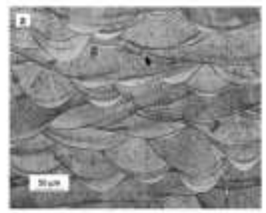


- Low Productivity
- More Maintenance
- Non-isotropic properties



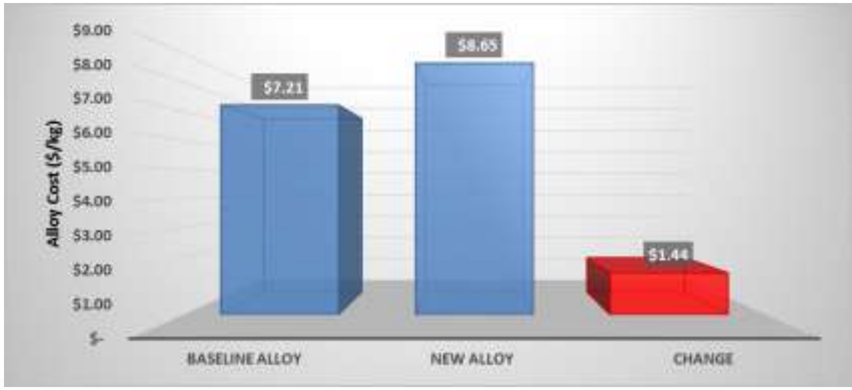
Binder Jetting | Laser

	Binder Jetting	Laser
1 Part	32 Hours	160+ Hours
4 Parts	~35 Hours	200+ Hours



Comparison of different AM processes

Cost of AFA alloy developed at ORNL



Progress- Development of cost model

Small Operation

- Productivity: 2,400 in^3/day
- Operating Cost: $70k/year ($191/day)
- Personnel Cost: $100K/year ($273/day)
- Energy Cost: $100/day
- Total Cost: $565.75/day
- Cost per in^3: $0.24

Medium Operation

- Productivity: 16,200 in^3/day
- Operating Cost: $105k/year ($288/day)
- Personnel Cost: $300K/year ($822/day)
- Energy Cost: $200/day
- Total Cost: $1,309/day
- Cost per in^3: $0.08

Large Operation

- Productivity: 113,400 in^3/day
- Operating Cost: $190k/year ($520/day)
- Personnel Cost: $1.6M/year ($4,383/day)
- Energy Cost: $500/day
- Total Cost: $5,404/day
- Cost per in^3: $0.05

Market Applications

ISOTHERM, INC.
ENHANCED HEAT TRANSFER

BraytonEnergy

bosal

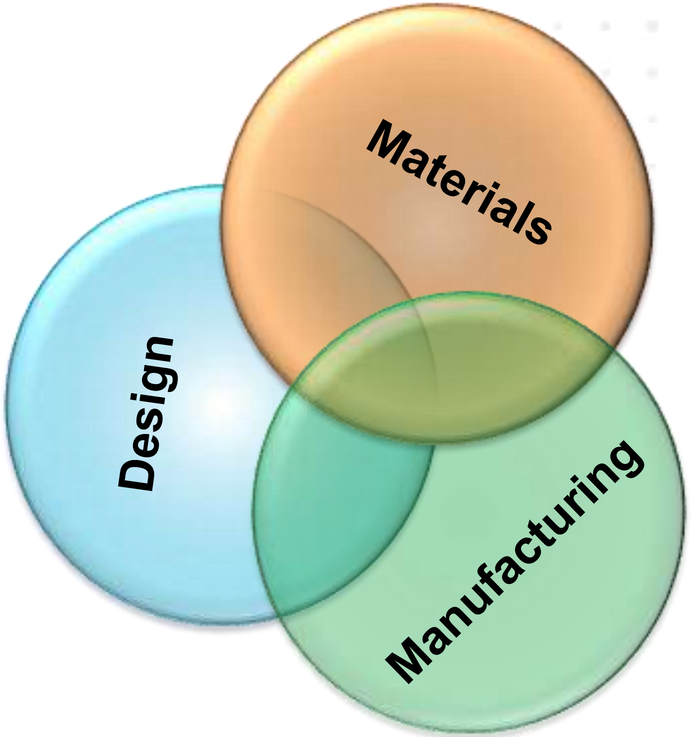
BOEING

ATREX ENERGY
POWERFUL POSSIBILITIES

- Modular power generation/concentrating solar
- Aerospace- Gas turbine engines/hybrid electric propulsion
- Nuclear- VHTR/Molten salt reactors
    - Transformational Challenge Reactor

Risks

- Design process, materials selection and manufacturing process are interdependent.
- High-temperature materials in general have low thermal conductivity.
- Presence of moisture in working fluids can cause material degradation.
- 3D printing with ceramic materials is a nascent area. Process optimization is needed to achieve topographical features and hermetically seal.
- A trade-off between design, manufacturing process and performance is mandatory to achieve a low-cost device.
- System integration of different hybrid power systems consisting of the heat exchangers.



THANK YOU

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